USACERL TECHNICAL REPORT M-91/14
January 1991

US Army Corps
of Engineers
Construction Engineering
Research Laboratory

Large Space Structures Fielding Plan

by
Charles C. Lozar
Alvin Smith
Andre N. Brackens

As the U.S. space program advances, there will be a need for large space structures (LSS) to support different missions. The construction of extraterrestrial LSS, whether in orbit or on the surface of another body, requires the preparation and execution of exquisitely detailed plans. Requirements for the LSS—the high degree of reliability, the interface with other nodes of the overall operation, and effective contingency plans—all point to the many integration activities that must occur before and during construction.

This study develops the preliminary plan for identifying efforts that will be required for LSS construction to support future Army initiatives in space. It provides a logical sequence of steps that can be followed whether the LSS is to be a platform (unmanned) or a station (manned). To develop this plan, some documents from the National Aeronautics and Space Administration (NASA) were consulted; however, it should be noted that, in many areas, no reference documents exist.

The complexity of this fielding plan suggested that an automated version would make it easier to implement. Such a computer-based program should consist of a hierarchical, multiple-track format and should be designed to serve developers at the top level (overall management scheme) to lower levels (detailed, engineer usable information).

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REPORT DOCUMENTATION PAGE

Form Approved
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1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	January 1991	Final

4. TITLE AND SUBTITLE

Large Space Structrures Fielding Plan

5. FUNDING NUMBERS

PE 4A162731
PR AT41
TA E
WU 056

6. AUTHOR(S)

Charles C. Lozar, Alvin Smith, and Andre N. Brackens

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

U.S. Army Construction Engineering Research Laboratory (USACERL)
PO Box 4005
Champaign, IL 61824-4005

8. PERFORMING ORGANIZATION REPORT NUMBER

TR M-91/14

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

HQUSACE
ATTN: CERD-M
20 Massachusetts Avenue, NW.
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

Copies are available from the National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

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This study develops the preliminary plan for identifying efforts that will be required for LSS construction to support future Army initiatives in space. It provides a logical sequence of steps that can be followed whether the LSS is to be a platform (unmanned) or a station (manned). To develop this plan, some documents from the National Aeronautics and Space Administration (NASA) were consulted; however, it should be noted that, in many areas, no reference documents exist.

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14. SUBJECT TERMS

large space structures

15. NUMBER OF PAGES

54

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std 239-18
298-102

FOREWORD

This research was conducted by the U.S. Army Construction Engineering Research Laboratory (USACERL) for the Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162731AT41, "Military Facilities Engineering Technology"; Technical Area E, "Echelons Above Corps Support"; Work Unit 056 "Construction Technologies and Methodologies for Space." The HQUSACE technical monitor was George Aitkens, CERD-M.

The initial work was performed by the USACERL Engineering and Materials Division (EM). Dr. Charles C. Lozar is president of Architects Equities, Champaign, IL, and participated in this study under contract to USACERL. Follow-on studies were conducted and the framework of an automated version was developed by Andre N. Brackens, USACERL research assistant from the University of Illinois, Urbana-Champaign. Dr. Paul A. Howdyshell is Acting Chief, USACERL-EM.

COL Everett R. Thomas is Commander and Director of USACERL, and Dr. L.R. Shaffer is Technical Director.

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LARGE SPACE STRUCTURES FIELDING PLAN

1 INTRODUCTION

Background

With the resurgence of the U.S. space shuttle program, the need for large space structures (LSS) to support increasingly complex missions is imminent. Recognizing the potential for LSS in both space exploration and national defense, the Department of Defense (DOD) is studying the most feasible approach to providing manned and unmanned facilities.

The U.S. Army Corps of Engineers (USACE) is responsible for construction within the Army and Air Force. As such, it constructs facilities to meet military requirements in all types of environments. However, the extraterrestrial environment is an entirely new frontier, with little known about the behavior of structures and issues related to material/design. To gain support in this area, USACE has designated the U.S. Army Construction Engineering Research Laboratory (USACERL) as the center for coordinating construction research. In 1987, a USACERL Technical Report was published to provide comprehensive background information on current technologies that could apply to LSS.[1] All work within DOD, USACE, and USACERL is being coordinated with other affected agencies such as the National Aeronautics and Space Administration (NASA), Strategic Defense Command (SDC), Army Materiel Command (AMC), and Army Training and Doctrine Command (TRADOC).

A critical part of development and deployment of LSS is to establish a fielding plan that will serve as a systematic procedure for conducting these efforts. Reviews of the literature and the criteria developed for NASA reveal that, although LSS construction has been conceptualized by artists for various presentations, little organized work has been done to document the actual sequence of events that must occur to place an LSS into orbit around the Earth. Such a plan is required to give developers a "roadmap" for fielding unfamiliar structures in an untested environment.

Objective

The objective of this work was to develop a preliminary plan identifying the key steps and sequence of activities for fielding an LSS. The ultimate goal of such a plan is to minimize risk and ensure cost-effectiveness of the LSS.

Approach

Because there is very little flight experience for LSS, literature describing an actual attempt or plan to place such a structure into space is very limited. Therefore, much of the information for this fielding plan was taken from other sources—in particular NASA documents, which define the sequence of design

[1] C.C. Lozar and L. D. Stephenson, State-of-the-Art Technologies for Construction in Space: A Review, Technical Report M-87/17/ADA188412 (U.S. Army Construction Engineering Research Laboratory [USACERL], September 1987).

and fabrication steps that must be followed as the basis for any experiment in space. These steps are generic to the space industry, and to a great extent reflect the safety, quality assurance, and verification plans that NASA has used on previous projects.

The fielding plan was developed as a flowchart of activities. Each major step is summarized in Chapter 2. The plan was designed as a very basic roadmap for LSS development. It is intended that the user obtain whatever information is necessary to design the LSS and tailor a specific fielding plan with the lift vehicle sponsor. Design considerations will include the carrier's capacity and requirements for ground processing and mating of parts before launch. Since these parameters will vary for different types of LSS and launch vehicles, the user should understand that the basic fielding plan will have to be continuously redesigned to provide an acceptable version for the specific operation.

Scope

This preliminary fielding plan is intended to be as broad as possible in scope. It offers numerous considerations for conditions and situations that relate to manned, rather than unmanned, orbital spacecraft. Platforms, which are unmanned, will be much less complex and a fielding plan for platforms would be somewhat simplified from the plan developed here.

The data and estimations in the fielding plan represent the best available at present and may not apply to every mission. In addition, these steps are to serve as a baseline only, with a specific plan to be developed for each LSS project.

Mode of Technology Transfer

The information in this report will impact the planning and execution of LSS construction on orbit. It will form the basis for construction CPM charts as well as the contents of Technical Data Packages for specific large space structures.

2 DESCRIPTION OF THE PLAN

Overview

The LSS fielding plan is designed as a flow diagram (Figure 1), with the main activities shown in the top line. Under these main activities are boxes containing many of the specific issues that must be addressed. These boxes are interconnected by solid and dotted lines with arrows indicating the probable flow of action in one box to the next level or aspect to be considered. Below the specific issues are boxes containing items such as secondary analyses, integration interfaces, and verification, quality assurance (QA), and quality control (QC) considerations. The two final lines reference existing NASA and DOD documents.*

Each main activity is discussed in this chapter. It should be noted again that this fielding plan is preliminary and will be augmented as more data and knowledge are gained.

LSS Mission Definition

General Approach

The mission definition component of the LSS fielding plan consists of items common to certain types of orbiting stations and platforms. The assumption is that the design will begin with a reference baseline LSS system that exists as a schematic or concept description. The joints, struts, utility trays, radiators, rotary joints, and similar items form the main structural skeleton for the LSS, which is followed throughout the diagram (i.e., by commonality of parts). The questions of pointing and control systems for the overall structural component, and the interface with other systems and subsystems become critical for determining which design parameters and variables would be most compatible with the objectives of the mission payload.

Functional Requirements

Purpose

The Functional Requirements section identifies both the managerial and engineering plans that consider the relationship between mission requirements and LSS components. At this stage, the feasibility of fielding an LSS must be evaluated initially and the decision made on how to proceed. The items listed under Mission Definition must be evaluated to determine the capability to fabricate and integrate the LSS, as well as the overall parameters and constraints for both the lift vehicle and orbit conditions.

Construction Loop

Under broad the category of Functional Requirements, a major component is the construction "loop" for LSS assembly. In this loop, decisions are made about the basis for procedures, extravehicular activity

* The Bibliography is a comprehensive list of documents used in developing the fielding plan.

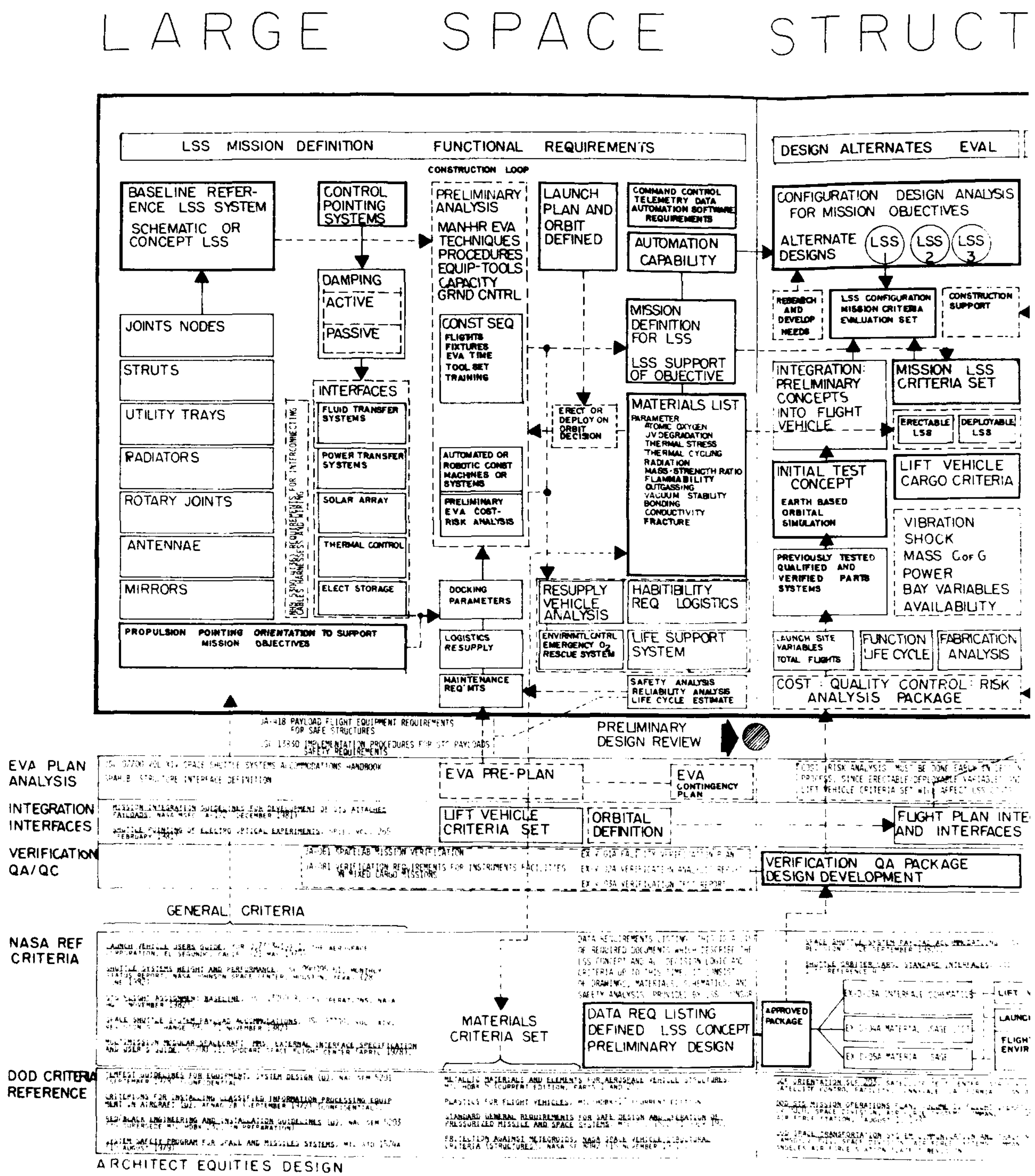
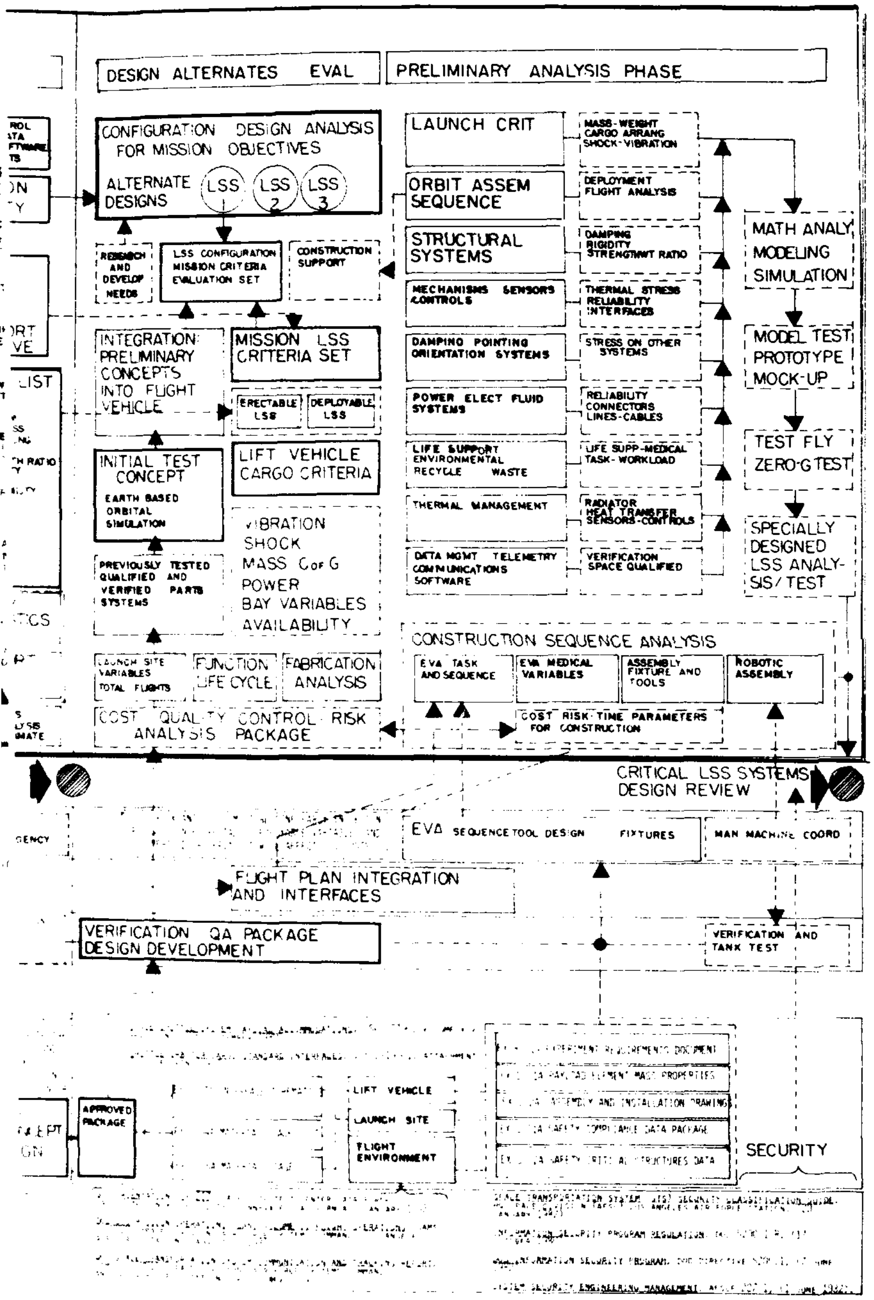


Figure 1. LSS fielding plan.

STRUCTURE (LSS)



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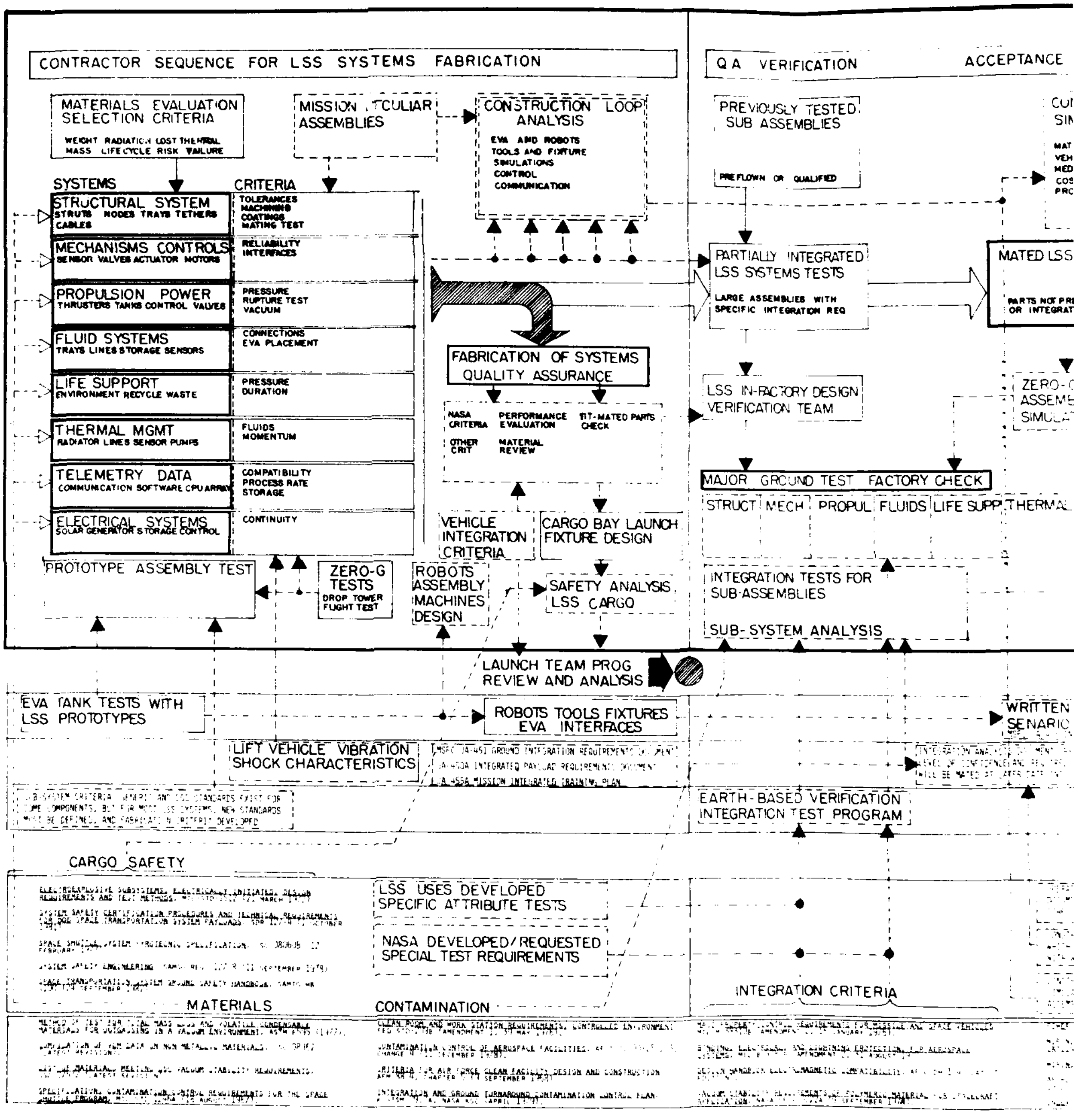
fielding plan.

FIELDING PLAN



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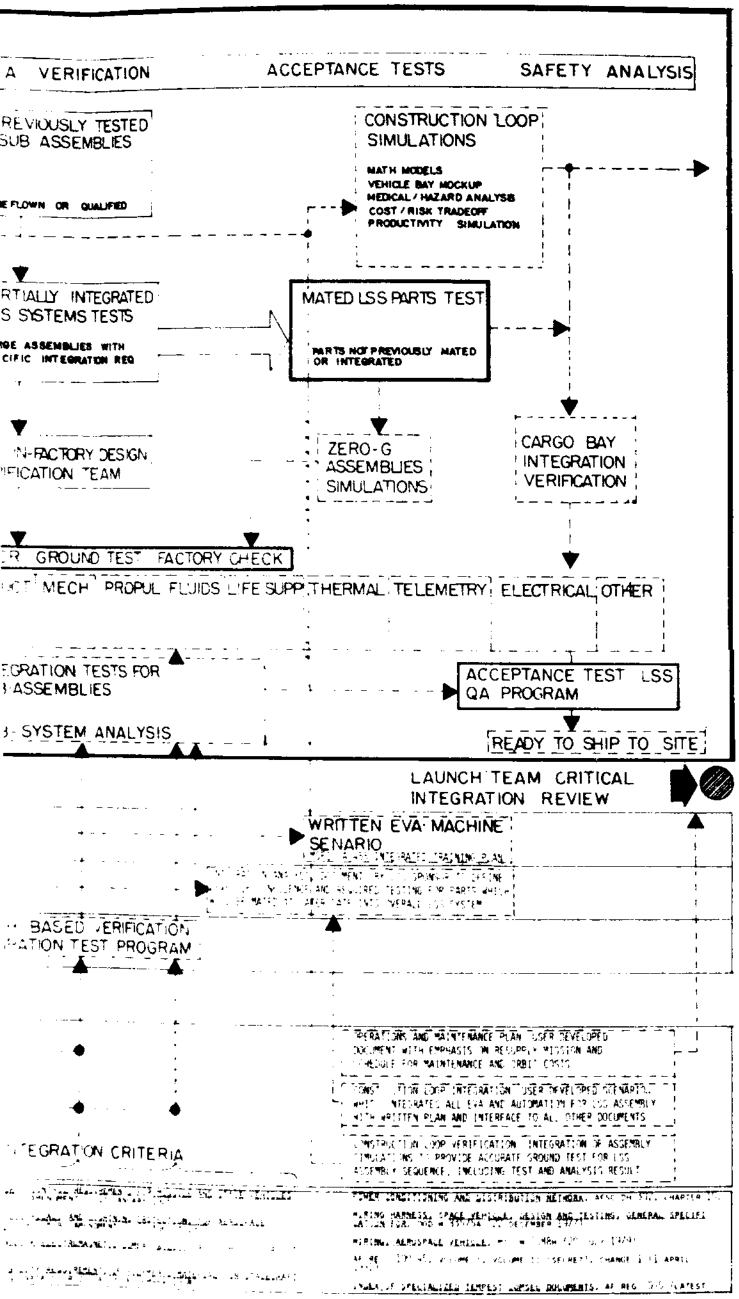
A VERIFICATION
ACCEPTANCE TESTS
SAFETY ANALYSIS
REVIOUSLY TESTED SUB ASSEMBLIES
CONSTRUCTION LOOP SIMULATIONS
MATH MODELS
VEHICLE BAY MOCKUP
MEDICAL / HAZARD ANALYSIS
COST / RISK TRADEOFF
PRODUCTIVITY SIMULATION
RTIALLY INTEGRATED
S SYSTEMS TESTS
MATED LSS PARTS TEST
PARTS NOT PREVIOUSLY MATED OR INTEGRATED
N-FACTORY DESIGN
FICATION TEAM
ZERO-G ASSEMBLIES SIMULATIONS
CARGO BAY INTEGRATION VERIFICATION
GROUND TEST FACTORY CHECK
MECH
PROPUL
FLUIDS
LIFE SUPP
THERMAL
TELEMETRY
ELECTRICAL
OTHER
EGRATION TESTS FOR
ASSEMBLIES
ACCEPTANCE TEST LSS
QA PROGRAM
SYSTEM ANALYSIS
READY TO SHIP TO SITE
LAUNCH TEAM CRITICAL INTEGRATION REVIEW
WRITTEN EVA MACHINE SENARIO
BASED VERIFICATION
ATION TEST PROGRAM
EGRATION CRITERIA

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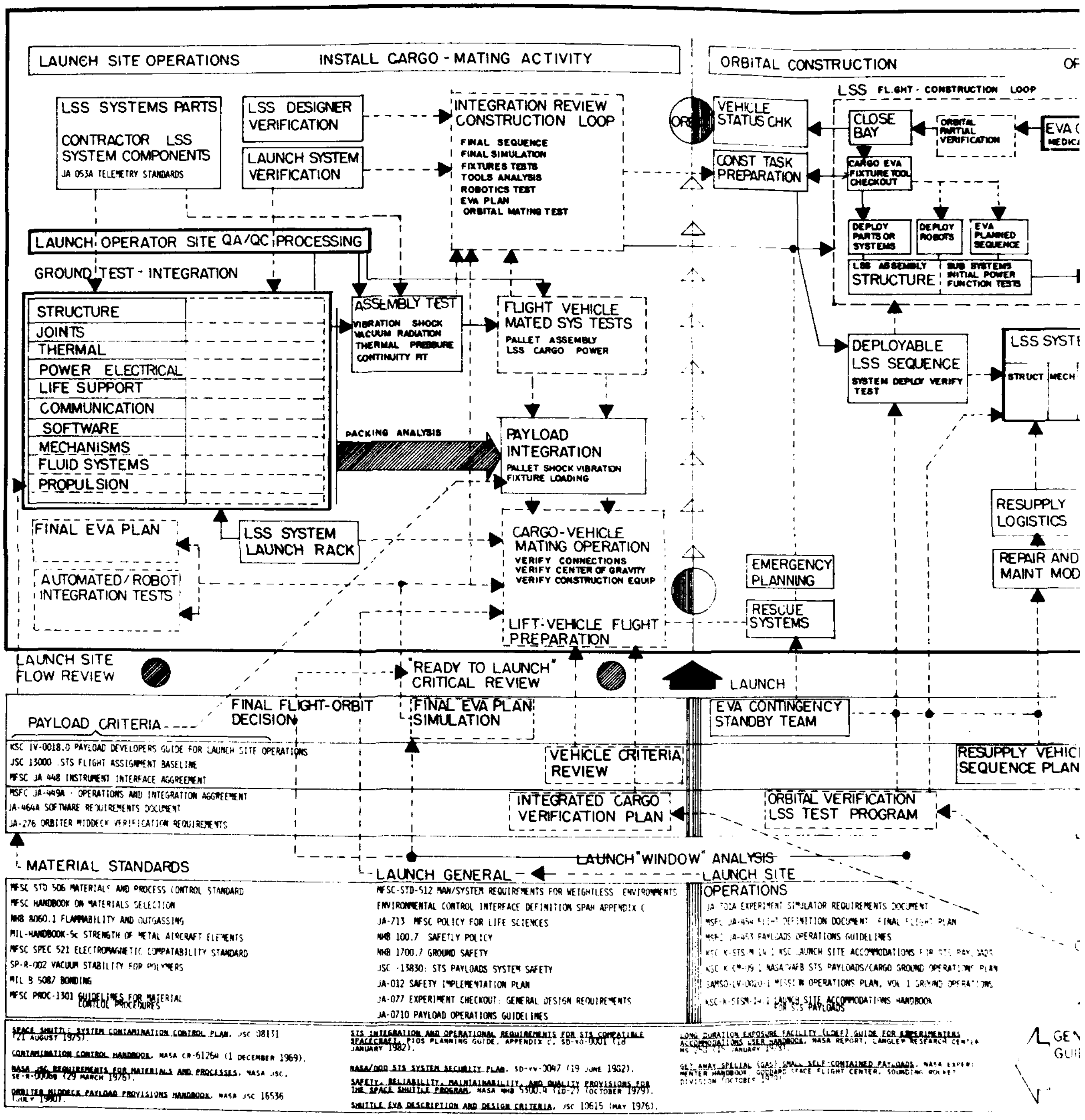

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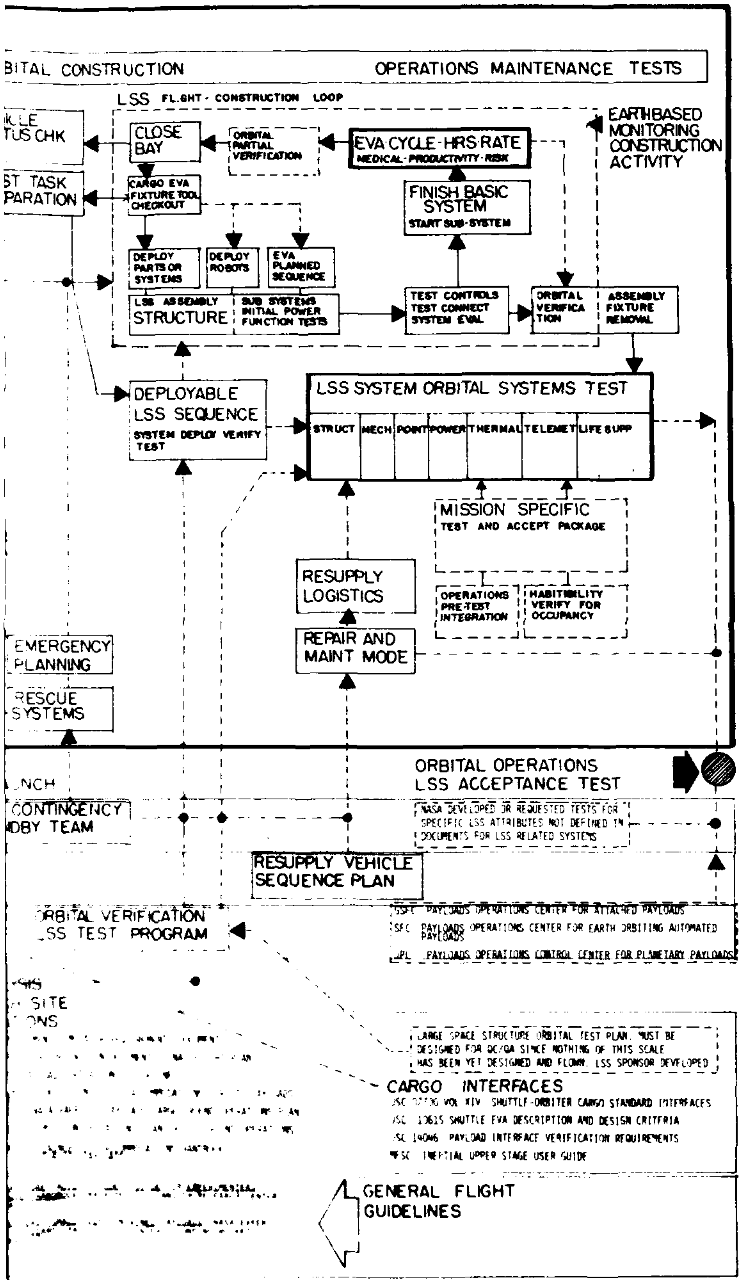

BITAL CONSTRUCTION
OPERATIONS MAINTENANCE TESTS
LSS FL.GHT - CONSTRUCTION LOOP
EARTHBASED MONITORING CONSTRUCTION ACTIVITY
TUS CHK
CLOSE BAY
ORBITAL PARTIAL VERIFICATION
EVA CYCLE - HRS RATE
MEDICAL - PRODUCTIVITY - RISK
ST TASK PARATION
CARGO EVA FIXTURE TOOL CHECKOUT
FINISH BASIC SYSTEM
START SUB - SYSTEM
DEPLOY PARTS OR SYSTEMS
DEPLOY ROBOTS
EVA PLANNED SEQUENCE
LSS ASSEMBLY STRUCTURE
SUB SYSTEMS INITIAL POWER FUNCTION TESTS
TEST CONTROLS TEST CONNECT SYSTEM EVAL
ORBITAL VERIFICA TION
ASSEMBLY FIXTURE REMOVAL
DEPLOYABLE LSS SEQUENCE
SYSTEM DEPLOY VERIFY TEST
LSS SYSTEM ORBITAL SYSTEMS TEST
STRUCT
MECH
POINT
POWER
THERMAL
TELEMET
LIFE SUPP
MISSION SPECIFIC
TEST AND ACCEPT PACKAGE
RESUPPLY LOGISTICS
OPERATIONS PRE-TEST INTEGRATION
HABITABILITY VERIFY FOR OCCUPANCY
REPAIR AND MAINT MODE
EMERGENCY PLANNING
RESCUE SYSTEMS
ORBITAL OPERATIONS
LSS ACCEPTANCE TEST
CONTINGENCY
DBY TEAM
NASA DEVELOPED OR REQUESTED TESTS FOR SPECIFIC LSS ATTRIBUTES NOT DEFINED IN DOCUMENTS FOR LSS RELATED SYSTEMS
RESUPPLY VEHICLE SEQUENCE PLAN
ORBITAL VERIFICATION
LSS TEST PROGRAM
GSFC PAYLOADS OPERATIONS CENTER FOR ATTACHED PAYLOADS
SFC PAYLOADS OPERATIONS CENTER FOR EARTH ORBITING AUTOMATED PAYLOADS
JPL PAYLOADS OPERATIONS CONTROL CENTER FOR PLANETARY PAYLOADS
SITE
ONS
LARGE SPACE STRUCTURE ORBITAL TEST PLAN. MUST BE DESIGNED FOR QC/QA SINCE NOTHING OF THIS SCALE HAS BEEN YET DESIGNED AND FLOWN. LSS SPONSOR DEVELOPED
CARGO INTERFACES
JSC 07700 VOL XIV SHUTTLE-ORBITER CARGO STANDARD INTERFACES
JSC 10615 SHUTTLE EVA DESCRIPTION AND DESIGN CRITERIA
JSC 14046 PAYLOAD INTERFACE VERIFICATION REQUIREMENTS
MSC INERTIAL UPPER STAGE USER GUIDE
GENERAL FLIGHT GUIDELINES

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(EVA), and robotic assembly that will be necessary to fabricate the LSS in space. The loop is introduced at this point and will continue through all stages of the LSS fielding plan to provide a basis for estimating the actual in-space activity needed for deployment or fabrication. This loop concept also involves a determination of methods for controlling and managing assembly of all systems.

The other components under Functional Requirements are general in nature, consisting of factors that must be considered in the earliest stages of determining how to field an LSS. Of special note are those elements concerned with safety, reliability, materials choice, command and control, and resupply and maintenance analysis for the operable LSS. It is important that these factors are considered during initial design so that various cost-related decisions based on deployment parameters can be evaluated later. Most of these elements are based on documents that provide narrative descriptions of concepts, which are supported by some limited numerical analytical techniques.

Mission Peculiar Activity

Each LSS must be assumed to have specific characteristics that relate to the objectives stated for its mission. Certain components of an LSS system may be standardized, but there may be other components that will be very peculiar to the mission. These components must be identified early in the Functional Requirements stage and developed as the user proceeds through the fielding plan. Specific mission attributes can magnify problems and costs in later development, especially if their discovery requires alterations and looping back to earlier stages. The extra costs and contingencies involved in addressing mission-peculiar activities at this stage will be an investment in cost-avoidance later and should be considered part of the development plan for fielding LSS.

Equipment in Support of Objective

It is important at this stage to define the type and capacity of the lift vehicle (shuttle or unmanned rocket) and the possible sequence of launches that will be required to field the entire LSS if all components cannot be transported in a single trip. Although it may seem premature to study this issue so early in the LSS development, it is essential that all LSS variables be brought to light at this point for effective decision-making. As indicated in other boxes of the diagram, extensive written and mathematical analyses such as trade-off studies and simplexes may be required to support decisions related to equipment.

Interface Requirements

In the earliest stages of the fielding plan, it is important to identify how interfaces will occur. Besides the obvious need to determine interfaces between the LSS subsystems (e.g., power transfer and fluid transfer systems), this analysis must consider how the command and control systems, automation, and ground support/safety measures in space will interface. Although these features can be developed to some degree as stated objectives, many must be designed from the ground up. To provide a complete conceptual definition of the mission, objectives, and functional requirements, a supplementary interface documentation plan is required. This plan is shown in Figure 1 toward the bottom of the first page and is called a Data Requirements Listing (by NASA). The Data Requirements Listing is a complete set of specifications, standards, and reference data as well as the exact records that must be kept on all components. This document must be submitted for approval during the preliminary design review. The LSS designer must prepare the Data Requirements Listing with an eye toward providing the most workable, cost-effective solution.

Design Alternatives Evaluation

Configuration Choices

At this point, many of the operational criteria and probable variables will have been defined in the Mission Definition and Functional Requirements stages. There may be more than one configuration for an LSS that could meet these initial requirements. Therefore, all possible managerial and design options must be addressed using baseline criteria for making acceptable choices. Figure 1 shows some of these choice criteria. Included are lift vehicle cargo criteria, the mission criteria set, launch site variables, fabrication analysis, functional life-cycle, and costs. These factors all interface with previous decisions. They must be addressed at this point to define the best possible choices before proceeding with further analyses. The criteria reference documents listed in Figure 1 may be available from NASA or DOD. In some cases, new studies may have to be performed specifically to develop criteria for unusual LSS configurations.

Integration Analysis

Integration is the assurance that the entire set of components and systems to comprise the LSS are designed to fit, and will fit, or mate with each other and with the cargo vehicle selected. Therefore, an initial analysis of integration capability and verification needs to be performed at this time. This analysis should produce a plan for verifying QA and should be completed early in the design alternatives evaluation phase. The designer will usually generate the verification plan for the LSS system, whereas the launch site verification plan must be a cooperative effort between the designer and the launch site operator.

Construction Analysis

A preliminary construction analysis loop (indicated by the dashed line in Figure 1) tracks through the entire second phase of design. This construction analysis helps determine the eventual cost for EVA as well as the best trade-offs between human and machine assembly methods. Risk factors and the availability of fixtures and tools are included in this analysis. Also at this phase, an initial study of the various tools and/or robots that will be needed for construction is conducted. Appropriate construction simulations necessary for EVA or robot assembly must be identified. Construction simulations include computer modeling, ground-based evaluations (e.g., neutral buoyancy tests) and similar activities that represent some or all aspects of on-orbit construction *before* it occurs.

Preliminary Systems Analysis

By this stage of the plan, many of the early conceptual choices have been made and it becomes necessary to define the steps that will be used to provide an analytical "proof of concept." Each separate major construction and deployment element for systems and subsystems of the LSS must be conceptually developed and analyzed. Various criteria documents will need to be consulted for methods of mathematical analysis, modeling, simulation, and other types of testing activities that must be completed. The results of these analyses provide the basis for making choices that represent the lowest risk and cost for the LSS being developed. At the end of this phase, there must be a Critical Design Analysis Review for the overall system. The "critical" review, as defined by NASA, includes all parties involved in the design, fabrication, testing, launch, and orbital management of an LSS.

Contractor Sequence for Systems Fabrication

This phase of development involves an evaluation of criteria that will dictate what systems/subsystems are fabricated. There are two main considerations here: materials selection and performance criteria for the systems and materials. Each of these elements may have been determined previously either by tests or by analyses done in another study.

Materials for LSS

Because of atomic oxygen degradation, radiation, anu the vacuum environment, materials choices can dramatically affect life-cycle costs and mission effectiveness. Thermal cycling and launch weight must also be considered in materials selection. The materials selected must be included for evaluation in the overall verification plan.

Systems for LSS

At this point, many of the interfaces between the LSS system and subsystems must be defined and coordinated to minimize expensive alteration costs. The fabrication process begins by defining scopes of work for contracts to firms with appropriate expertise in each component area. These contracts must be coordinated by the LSS project manager. Because of the effort involved in administering these contracts, it is important to realize that many of the tests for integration and verification must be done (even on the basis of partial assemblies) during the fabrication phase.

Fabrication

Systems fabrication must be reviewed in terms of the vehicle integration criteria and launch fixture design as well as the compatibility issue. The considerations described earlier in the construction "loop" analysis must be evaluated again during the fabrication sequence to determine if the final product will permit construction activities to occur in space. These considerations must be carried through each stage of the LSS development (hence the "loop" terminology).

The effort involved in fabrication control can be extensive. However, it is justified in order to ensure quality and system integration into the LSS. In some cases, the verification and QA personnel from the LSS project office must work in the factory during the component processing phase to ensure contract compliance and that full integration of parts will be possible.

Quality Assurance Verification

Integration

QA verification requires the retesting of previously tested subassemblies to be used in the LSS. Partially integrated systems tests must be conducted before assembling the complete LSS. At this stage, integration is a somewhat general term that implies physical mating, flight dynamics, and performance c' aracteristics matching for all assemblies. This activity usually requires a written document for each launch item.

Verification

Major elements of the verification plan developed earlier now come into play. Those aspects that will verify procedures, processes, and products must be addressed as the final fabricated items for the LSS are completed. Structural elements, subassemblies, and partially integrated systems all must be verified. Since an LSS has not been orbi'ed to date, it is apparent that the LSS designer will have had to develop a verification plan that is unique to both the specific LSS system and to the choice of materials and design methods. The verification plan that NASA developed for Space Station Freedom is the best guidance available at present. The final LSS plan will require extensive development and coordination.

Ground Tests

The size of an LSS generally precludes it from being tested extensively in space; moreover, space is a very hostile environment and such testing would incur an extraordinary cost. For these reasons, it is necessary to conduct as many ground tests and evaluations as possible. Time and cost can be reduced if this is done before the major assemblies leave the factory. Certain parts can be tested during both the verification process and the acceptance testing phase. Most of these tests can occur in the factory on partial assemblies; however, they should have been identified at an earlier stage (as has been discussed) based on performance criteria for the LSS and cargo bay integration requirements. Questions as to how much the test data can be generalized from partial to whole assemblies must be addressed and an agreement reached.

Acceptance Testing/Safety Analysis

Construction "Loop" Simulation

The earlier analyses involving the construction loop, final products of the fabrication, EVA vs. robotic productivity, risk tradeoffs, and cost must now be considered together. Construction loop simulations should be made a part of the acceptance tests for the fabricated items. These simulations must be done before beginning the final safety analysis that will occur prior to delivering the LSS parts and components to the launch site. Simulations with a prototype would be appropriate at this stage.

Mated Parts Test

At this time, parts that have not been together in one place (i.e., made in different parts of the country or by different fabricators) are finally assembled and checked for mating fit and tolerances. They are to be checked as assemblies and subassemblies, and are processed either as major ground test components or as part of final assemblies required directly or as inputs to simulations used to verify QA. Mated parts testing, with the variety of systems in an LSS, can require considerable time to accomplish.

Acceptance Testing

All major ground checks and acceptance tests, based on the earlier verification plan, must be performed before the LSS system is shipped to the launch site. The final "sign-off" from the fabricator to the LSS project manager is done before the process of integration into the launch vehicle begins. It is also at this time that the launch team begins its preliminary integration review covering the launch vehicle flight characteristics, cargo bay criteria, and dimensional requirements which must be met. These criteria were established early in the design phase; verification that the completed prototype parts meet the criteria is now required. This is the last chance to make fabrication changes before the LSS subassemblies and components are shipped to the launch site.

Launch Site Operations

Processing and Packing

To ensure the safety and reliability of both the surrounding environment and the launch vehicle, the launch site operator must be given a great degree of control over the fabricated system components delivered to the site. QA and QC to ensure safety on the launch range are the launch operator's responsibilities. Therefore, the operator has the obligation, and usually the authority, to recheck the ground test integrations of various components and to conduct a preliminary review of the LSS assembly test for vibration, shock, and pressure that will occur when the vehicle is launched into space. This procedure helps to ensure that the cargo will not be a hazard to the launch vehicle. These considerations are used to develop a mathematical packing analysis for the payload in the cargo bay. It is the launch operator's responsibility to conduct the final tests or checks for matching and mating subsystems.

Payload Integration

Earlier in this chapter, certain levels of integration relating to the cargo bay were identified. Certain flight vehicle mated system tests must be conducted so that components of the space structure that require continuous power can be identified. Also, components that require automatic checking to ensure that they are still operational after the launch procedure may need to be pretested in a connected configuration between the flight vehicle and the cargo bay. The payload integration analysis also covers structural fixing of the pallet, container, or supports that will hold the components in place inside the vehicle as it goes into orbit. The launch shock and vibrational effects on components can be quite substantial; therefore, the launch site operator must verify the ability to withstand the various modes of loading through structural analysis of the assembled load and its supports.

Mating Operation

The final step in preparation for flight is the cargo mating operation, in which all connections and the manifest are verified, and the previously defined construction equipment and tools are ensured to be included on the flight. The final integration review for the construction "loop" is conducted as part of this activity, and may actually have been in progress for some time. Since the assembly of an LSS consists of several different types of construction efforts, it is quite possible that the construction loop analysis for each flight may be quite different from the others, depending on what is being assembled or integrated. Upon verification of the cargo vehicle mating operation, the launch operator will conduct a "ready-to-launch" critical review. The purpose of this review is to ensure the success both of the launch vehicle and the cargo it contains. Participants in this review should include representatives from all organizations involved in the LSS design and fabrication, lift vehicle personnel, and the launch site operator.

Orbital Construction

Sequence

Assume that launch has occurred, the vehicle is in the required orbit, and the initial phases of the construction "loop" can be conducted to construct the LSS. The decision has been made previously as to whether the LSS is to be assembled by an astronaut during EVA, a robot, or as a deployable structure. Whichever option was selected and planned earlier, a construction cycle begins, during which the activity will consist of assembling components and subsystems followed by tests of connections, electrical and fluids continuity checks, and final verification of the whole LSS assembly. Throughout this series of events, there will be an emphasis on EVA (if required) in terms of medical monitoring and analysis of human status. As part of the construction loop, Earth-based monitoring will be occurring and an emergency plan for rescue operations and other contingencies will be in effect. The construction sequence will have been determined in the fielding plan—from the initial analyses done in the first stage to the simulations completed during acceptance testing.

Assembly Processes

The assembly process at this point involves human-machine interfaces and verification for each step completed. It should be noted that this process has been "designed" on a conceptual basis; the realities of risk and medical hazards become very real as the actual LSS construction occurs.

Productivity

The productivity needed during orbital construction, when considered with the risk factors, will determine the effectiveness of the LSS fielding plan. As an underlying planning principle, productivity and risk analyses will have been occurring since the very first part of the design process and will have been important in all planning activities. Provisions should be made to record the actual productivity and identify any required deviations from the plan so that a valid experiential base for LSS construction during orbit will result. The results will aid in making better plans for future operations.

Orbital Verification

Systems that could not be tested previously under zero gravity and high-vacuum conditions in their mated states must be verified while in orbit. These tests and simulations will be part of the original verification plan. Efforts for orbital verification should be minimized since "verification" space is not a precise, tested concept. These activities can either be automated or conducted by astronauts. Orbital verifications represent the last step in an LSS assembly plan.

Testing, Operations, and Maintenance

Operational Tests

The LSS must be tested as an integrated system to assure that the resulting configuration will operate in orbit as designed and will support the initial mission objectives. This activity is part of the final acceptance testing. The relationship between operational acceptance tests by the LSS developer and the owner (operator) of the LSS platform need to be defined in the first phase of LSS design since turnover of the entire orbiting system will be a very important step. In other words, it must be clarified that the LSS design will not be accepted until it passes all operational tests; the basis of acceptability will have been accurately and completely understood as the design was developed.

Maintenance Analysis

Resupply logistics and repair/maintenance plans also will have been identified during the design process (see Figure 1). The sequence and schedule for the resupply vehicle, any docking parameters required, orbital transfer, and the contingency plan are documents that must be turned over to the on-orbit controller for operating and maintaining the LSS.

3 LSS FIELDING PLAN AUTOMATION

Objective of Automating the Plan

At present, there is no collation of all technologies that might apply to construction in space. The development of a Large Space Structure Fielding Plan took a step in that direction by organizing a preliminary "road map" for identifying efforts required for LSS construction in orbit. The plan is presented in Chapter 2 as a flow diagram of numerous interfacing activities with many variables and information flow that follows different paths. The complexity of this plan suggests that an automated version would make it easier to use. This chapter takes the initial steps in simplifying the flow diagram by organizing a management plan and installing the information on a machine. For simplicity, the information was organized using Wordperfect 5.0, Lotus 1-2-3, Apple MacIntosh MacDraft and MacProject, and Microsoft Excel.[2]

As the technology matures and the information and data references are filled in, this rudimentary plan can provide the basis, along with mission-specific information, for generating Critical Path Method (CPM) detailed plans.

Process Explanation

The organizational method used to automate the fielding plan is comparable to methods used for construction planning and control.

Using a construction project as an analogy, the objectives of the project (plans and specs) are identified to initialize the process. Work areas and activities are defined and from that point, cost estimates, material requirements, manhour requirements, and schedule parameters are determined using various project management methods. The LSS Fielding Plan incorporates the same logic that would be used on a terrestrial construction project; however, project management is made more complex by the following unique situations:

1. Material requirements (fabrication and performance)

2. Component delivery process (shuttle: capacity and expense)

3. Extravehicular Activity (EVA): (inherent danger of working in a hazardous environment).

These and many other unique situations must be considered while automating the fielding plan. However, at this level, the investigation is into an overall scenario and the development of a skeletal framework to be filled in as knowledge is gained. Since there is no precedent on which to base the plan, logic and comparison to terrestrial project management techniques were incorporated.

This phase breaks the existing fielding plan into manageable elements. These elements are based on hierarchial relationships, three of which of have been established: (1) work phases (2) activities and (3) tasks.

[2] Mention of tradenames does not constitute endorsement.

Work phases (assigned numeric codes) represent the initial breakdown of the overall plan from which seven categories have been identified. The numerical code used to designate the phases (05-35) is designated and spaced to allow for activities that may be determined or identified later.

05 LSS MISSION DEFINITION/FUNCTIONAL REQUIREMENTS

10 DESIGN ALTERNATIVES EVALUATION

15 CONTRACTOR SEQUENCE FOR LSS SYSTEM FABRICATION

20 QUALITY ASSURANCE VERIFICATION/ACCEPTANCE TESTS/SAFETY ANALYSIS

25 LAUNCH SITE OPERATIONS

30 ORBITAL CONSTRUCTION

35 OPERATIONS AND MAINTENANCE ACTIVITY

The second level of the breakdown hierarchy divides "work phases" into manageable elements that will be defined as **activities** and assigned alphabetic codes. Activities demonstrate the flexibility of defining a work breakdown structure. Several activities may be planned and the level of detail in which these activities are accomplished in terms of "phases" depends on the complexity of the project. This method of organization is ideal for an LSS Fielding Plan due to the complexity and vast coordination requirements of an LSS project.

The third level of the breakdown hierarchy divides "activities" into manageable elements that are defined as **tasks** and assigned numeric codes. For LSS fielding plan purposes, a task is a unique unit of work or decision making which may span several work areas (i.e., quality assurance and quality control checks).

Example: 05 WORK PHASE
A. Activity
1. Task

These three levels can provide management devices at the three degrees of need to know. For example, program managers may use the first two levels of the hierarchy to track project development. Project managers may use levels two and three to provide detailed insight into status. System or element performers may use level three, with supporting identified reference documents, as their detailed guidance and refer to levels two and one for sense as to where their work fits into the scheme of things.

Diagrammatic Work Breakdown Structure

The seven work phases identified in the previous section have each been arranged into individual flow charts. This arrangement provides a quick reference to relationships between activities and tasks with respect to a specific work area. It is designed to give a general indication of **precedence** between activities. The chart should be read from top to bottom and left to right. However, it should be noted that actual duration of tasks, which may vary to a large degree, depends on the specific mission. Immediately following the flow chart is a **spreadsheet** that examines each task in terms of qualification for completion, costs, time/duration, milestones, status, and references (see the Appendix for an explanation of each parameter). This study does not apply the duration parameter. Recently developed software uses "what if" mission scenarios sensitive to time, and other mission specific examples.[3]

The following text demonstrates each work phase of the LSS Fielding plan organized into a manageable work breakdown structure in (1) outline, (2) flow chart (diagrammatic), and (3) spreadsheet formats. The latter two are shown in Figures 2 through 7.

[3] Large Scale Programs Insitute (Austin, TX) Lunar Base Model (LBM) Version 3.0 is a PC-based mission planning and system integration tool that provides a quantitative assessment of lunar base program options.

05 LSS MISSION DEFINITION/FUNCTIONAL REQUIREMENTS

A. Define Purpose and Objective of Mission

1. State the requirements for the LSS
2. Identify items common to similar types of orbiting stations and platforms
3. Refer to baseline LSS system (schematic or conceptual) description

B. Establish Time, Feasibility, & Financial Parameters

C. Construction Loop for LSS Assembly

1. Establish basis for procedures and techniques
2. Decide on method of assembly (EVA) or necessary to fabricate LSS
3. Provide initial basis for estimates for the actual in-space activity of deployment or fabrication
4. Determine means of controlling or managing assembly of all systems

D. Mission Peculiar Activity Identification

1. Identify standardized components of the LSS system
2. Identify specific characteristics of LSS function (related to earlier stated objectives of the mission)

E. Functional Requirements

1. Identify and configure managerial plan
2. Identify and configure the engineering plan
3. Consider the relationship between the mission requirements and the components (material fabrication & performance requirements)

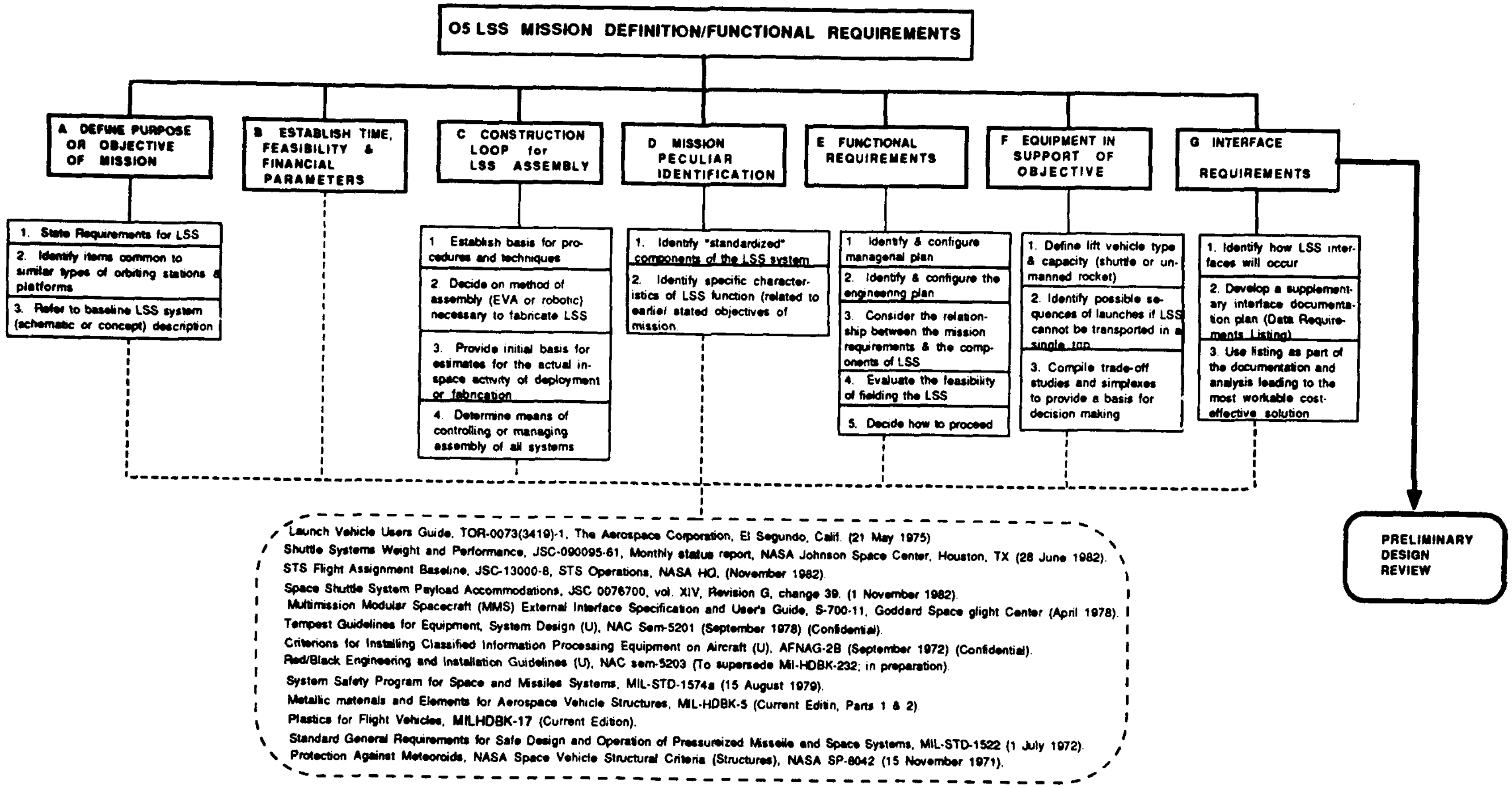
F. Equipment in Support of Objective

1. Define lift vehicle type and capacity (shuttle or unmanned rocket)
2. Identify sequences of launches if LSS cannot be transported in a single trip
3. Compile trade-off studies and simplexes to provide a basis for decision-making

G. Interface Requirements

1. Identify how LSS interfaces will occur
2. Develop a supplementary interface documentation plan (Data Requirements Listing)[4]
3. Use listing as part of the documentation and analysis leading to the most workable cost-effective solution

[4] Document requiring submitted and approval by NASA before the preliminary design review.



a. Flow chart

Figure 2. 05 LSS Mission Definition/Functional Requirements.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION EST.	DURATION ACT.	CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
A	Define Purpose									
B	Establish Time, Feasibility, & Financial Parameters									
C	Baseline reference LSS System									
D	Develop schematic/concept LSS									
E	Launch plan & orbit definition									
F	Automation Capability									
G	Construction Loop (EVA or Robotic Assembly)									
H	Materials List (Parameters)									
I	Equipment in support of objective									
J	Interface Requirements									
MILESTONE 1: PRELIMINARY DESIGN REVIEW										

b. Spreadsheet

Figure 2. (Cont'd).

10 DESIGN ALTERNATIVES EVALUATION

A. Configuration Choices

1. Examine alternative configurations of LSS that will meet mission objectives
2. Examine choice criteria (i.e., launch site variables fabrication analysis, etc...)

B. Design Analysis Objectives - Alternate Designs

1. Check design analysis of objectives and choice - criteria consistency
2. If analysis objectives and choice criteria are inconsistent, enter "loop" & examine alternate designs

C. Integration Analysis

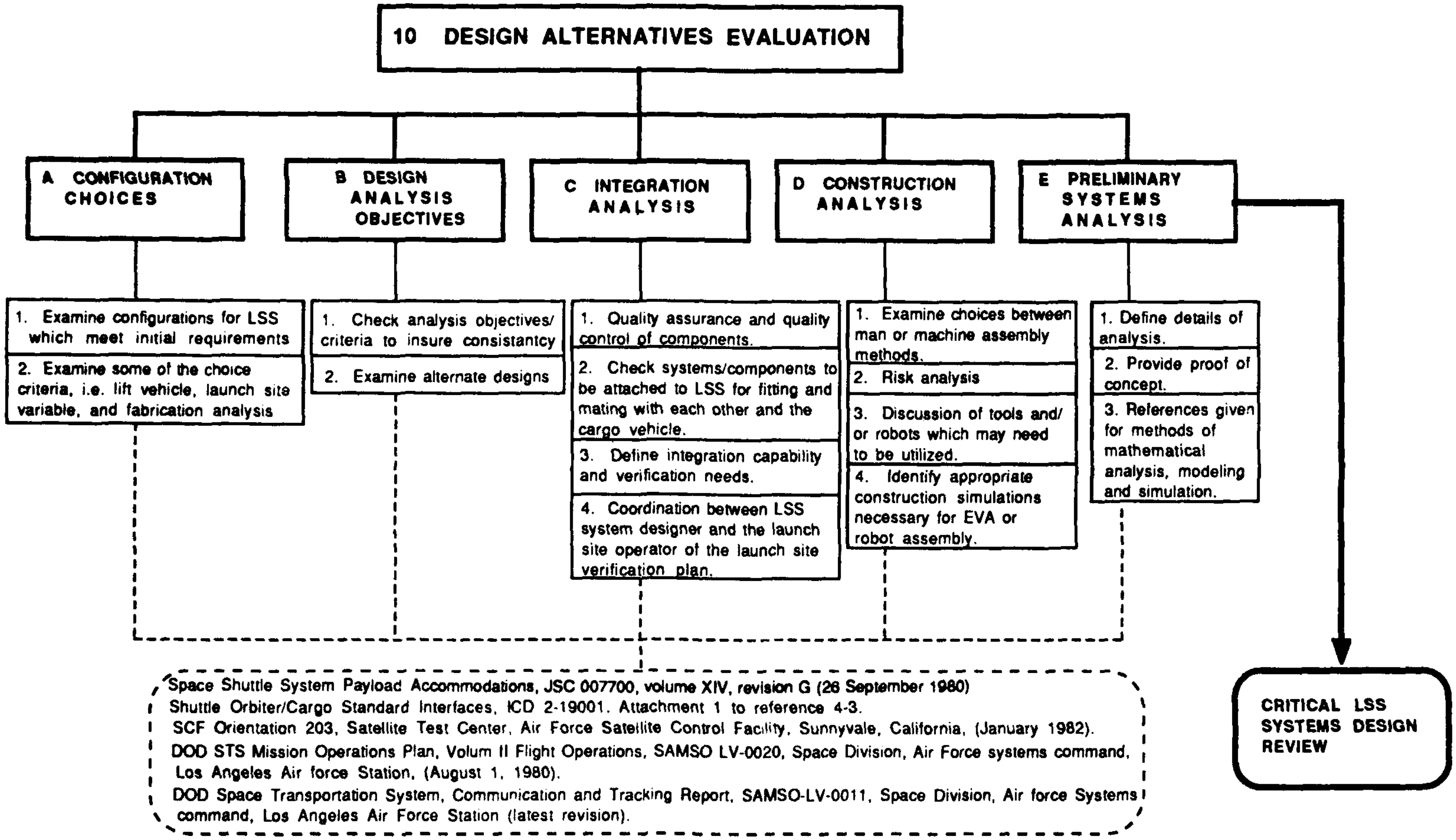
1. Perform quality assurance and quality control for components
2. Verify components and systems to be attached to LSS will fit with the LSS and with the cargo vehicle selected
3. Define integration capability and verification needs
4. Coordination launch site verification plan between the LSS system designer and the launch site operator

D. Construction Analysis

1. Examine trade assembly choices between man or machine assembly methods (erectable vs. deployable)
2. Conduct risk analysis
3. Determine what tools and/or robots will be needed
4. Identify appropriate construction simulations necessary for EVA or robot assembly

E. Preliminary System Analysis

1. Define detailed analysis steps
2. Perform analysis
3. Provide analytical proof of concept
4. Reference various criteria documents for methods of mathematical analysis, modeling and simulation



a. Flow chart

Figure 3. 10 Design Alternatives Evaluation.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION		CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
						EST.	ACT.			
A	Configuration Choices									
B	Design Analysis Objectives/Alternate Designs									
C	Integration Analysis									
D	Construction Analysis									
E	Preliminary Systems analysis									
MILESTONE 2: CRITICAL LSS SYSTEMS DESIGN REVIEW										

b. Spreadsheet

Figure 3. (Cont'd).

15 CONTRACTOR SEQUENCE FOR LSS SYSTEM FABRICATION

A. Material Evaluation and Selection Criteria

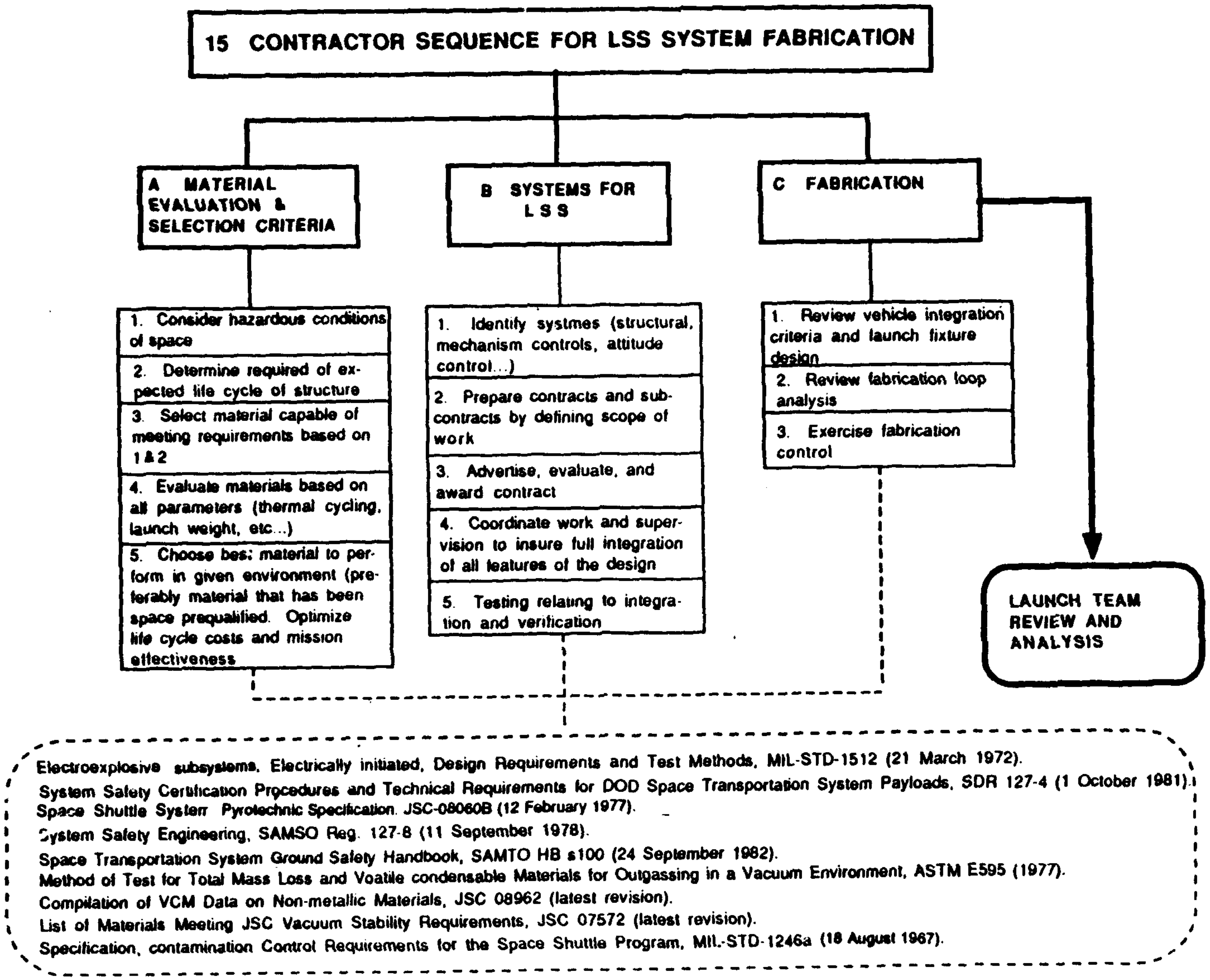
1. Consider hazardous conditions of space (atomic oxygen, temperature, etc.)
2. Determine required or expected life cycle of structure
3. Select material capable of meeting requirement based on (1&2)
4. Evaluate materials based on all parameters including thermal cycling and launch weight
5. Choose "best" material to perform in given environment (preferably material that has been preselected space (qualified)
6. Optimize life cycle costs and mission effectiveness

B. Systems for LSS

1. Identify systems (structural, mechanism controls, attitude control...)
2. Prepare contracts and subcontracts by defining scope of work
3. Advertise, evaluate, and award contract
4. Coordinate work and supervision to insure full integration of all features of the design
5. Conduct testing relating to integration and verification

C. Fabrication

1. Review vehicle integration criteria and launch fixture design
2. Review fabrication loop analysis
3. Exercise fabrication control



a. Flow chart

Figure 4. 15 Contractor Sequence for LSS System Fabrication.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION EST.	DURATION ACT.	CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
A	Materials Evaluation & Selection Criteria									
B	Systems for LGS (i.e., structural, mechanism									
	controls, propulsion power, fluid, life support,									
	thermal management, telemetry, electrical,									
C	Fabrication									
MILESTONE 3: LAUNCH TEAM REVIEW & ANALYSIS										

b. Spreadsheet

Figure 4. (Cont'd).

20 QUALITY ASSURANCE VERIFICATION/ACCEPTANCE TESTS/SAFETY ANALYSIS

A. Integration

1. Retest previously tested subassemblies
2. Test partially integrated systems
3. Check physical mating of all assemblies
4. Check flight dynamics of all assemblies

B. Verification

1. Base new verification on previously submitted verification plan
2. Verify structural elements, subassemblies, & partially integrated systems

C. Ground Testing

1. Identify partial assemblies in terms of performance criteria for LSS and cargo bay integration and verification
2. Determine what parts and/or partial assemblies may be tested in the factory
3. Address extrapolation of test data from partial to whole assemblies
4. Verify extrapolated test data by consensus

D. Construction "Loop" Simulation

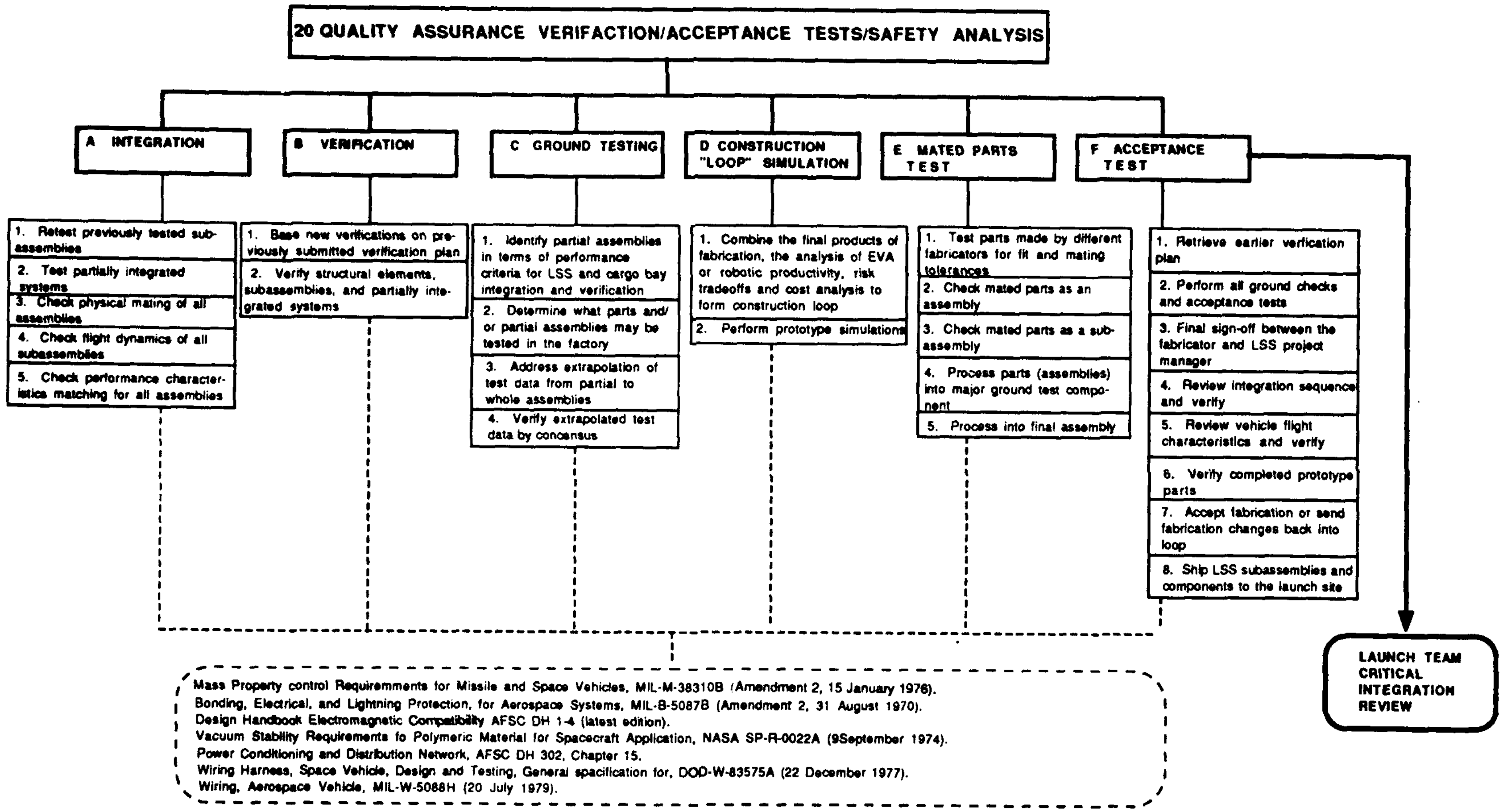
1. Combine the final products of fabrication, the analysis of EVA or robotic productivity, risk tradeoffs and cost analysis to form construction loop
2. Perform prototype simulations

E. Mated Parts Test

1. Test parts made by different fabricators for fit and mating tolerances
2. Check mated parts as an assembly
3. Check mated parts subassembly
4. Process parts (assemblies) into major ground test component
5. Process into final assembly

F. Acceptance Test

1. Retrieve earlier verification plan
2. Perform all ground checks and acceptance tests
3. Final sign-off between the fabrication and LSS project manager
4. Review integration sequence and verify
5. Review vehicle flight characteristics and verify
6. Verify completed prototype parts
7. Accept fabrication or send fabrication changes back into loop
8. Ship LSS subassemblies and components to the launch site



a. Flow chart

Figure 5. 20 Quality Assurance Verification/Acceptance Tests/Safety Analysis.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION		CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
						EST.	ACT.			
A	Integration									
B	Verification									
C	Ground Tests									
D	Construction "Loop" Simulation									
E	Mated Parts Test									
F	Acceptance Test									
MILESTONE 4: LAUNCH TEAM CRITICAL INTEGRATION REVIEW										

b. Spreadsheet

Figure 5. (Cont'd).

25 LAUNCH SITE OPERATIONS

A. Processing and Packing

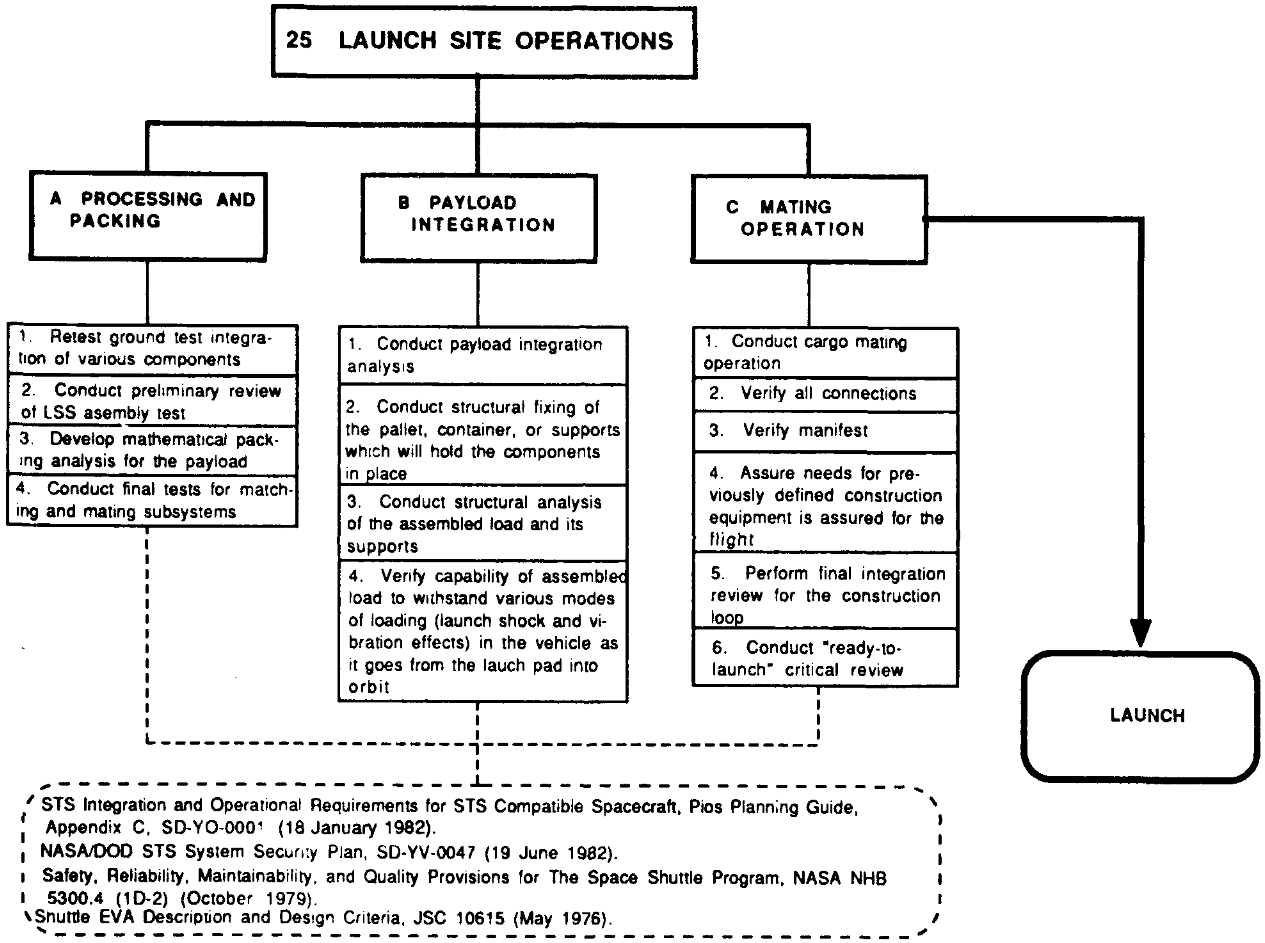
1. Recheck ground test integration of various components
2. Conduct preliminary review of LSS assembly test (vibration, shock, & pressure)
3. Develop mathematical packing analysis for the payload
4. Conduct final tests for matching and mating subsystems

B. Payload Integration

1. Conduct payload integration analysis
2. Conduct structural fixing of the pallet, container, or supports which will hold the components in place
3. Conduct structural analysis of the assembled load and its supports
4. Verify capability of assembled load to withstand various modes of loading (launch shock and vibration effects) in the vehicle as it goes from the launch pad into orbit

C. Mating Operation

1. Conduct cargo mating operation
2. Verify all connections
3. Verify manifest
4. Assure needs for previously defined construction equipment is assured for the flight
5. Perform final integration review for the construction loop
6. Conduct "road-to-launch" critical review



a. Flow chart

Figure 6. 25 Launch Site Operations.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION EST.	DURATION ACT.	CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
A	Processing & Packing									
B	Payload Integration									
C	Mating Operation									
MILESTONE 6: LAUNCH										

b. Spreadsheet

Figure 6. (Cont'd).

30 ORBITAL CONSTRUCTION

A. Assembly Process and Sequencing

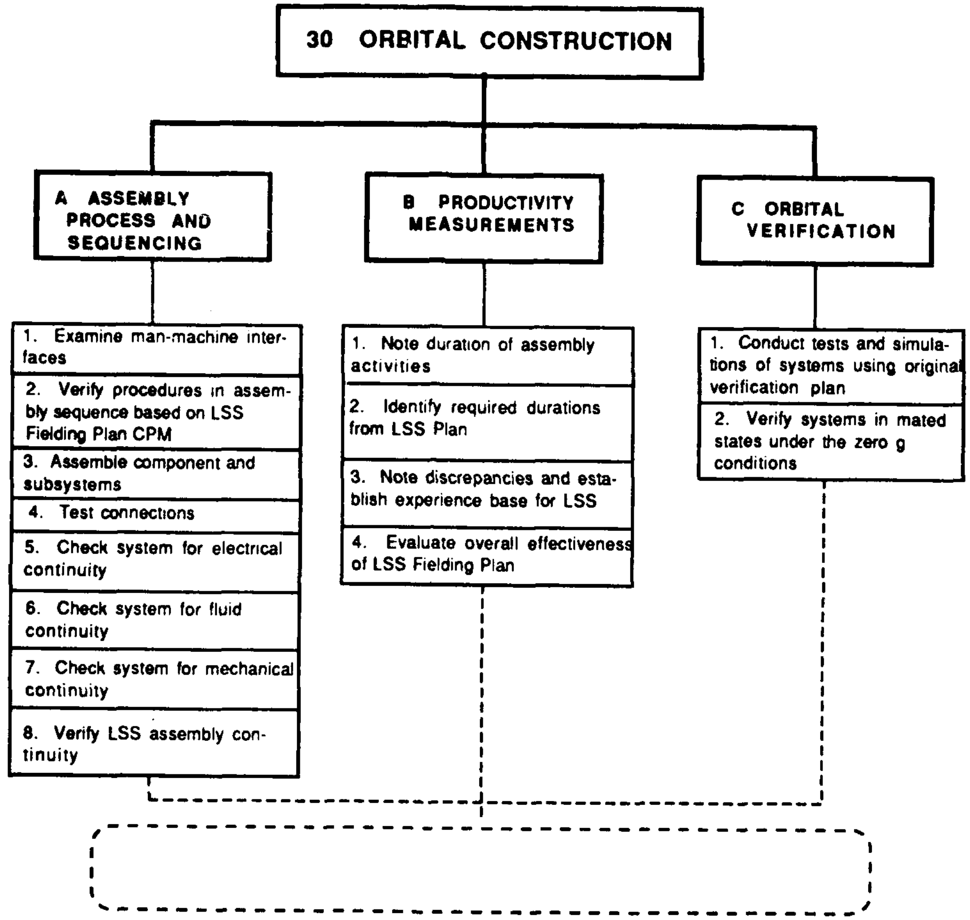
1. Examine man-machine interfaces
2. Verify procedures in assembly sequence based on LSS Fielding Plan CPM
3. Assemble components and subsystems
4. Test connections
5. Check system for electrical continuity
6. Check system for fluid continuity
7. Check system for mechanical continuity
8. Verify LSS assembly continuity

B. Productivity Measurements

1. Note duration of assembly activities
2. Identify required durations form LSS Plan
3. Note discrepancies and establish experience base for LSS
4. Evaluate overall effectiveness of LSS Fielding Plan

C. Orbital Verification

1. Conduct test and simulations of systems using original verification plan
2. Verify systems in mated states at zero g.



a. Flow chart

Figure 7. 30 Orbital Construction.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION		CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
						EST.	ACT.			
A	Sequence									
B	Assembly Processes									
C	Producibility									
D	Orbital Verification									
MILESTONE 8: CONSTRUCTION COMPLETION										

b. Spreadsheet

Figure 7. (Cont'd).

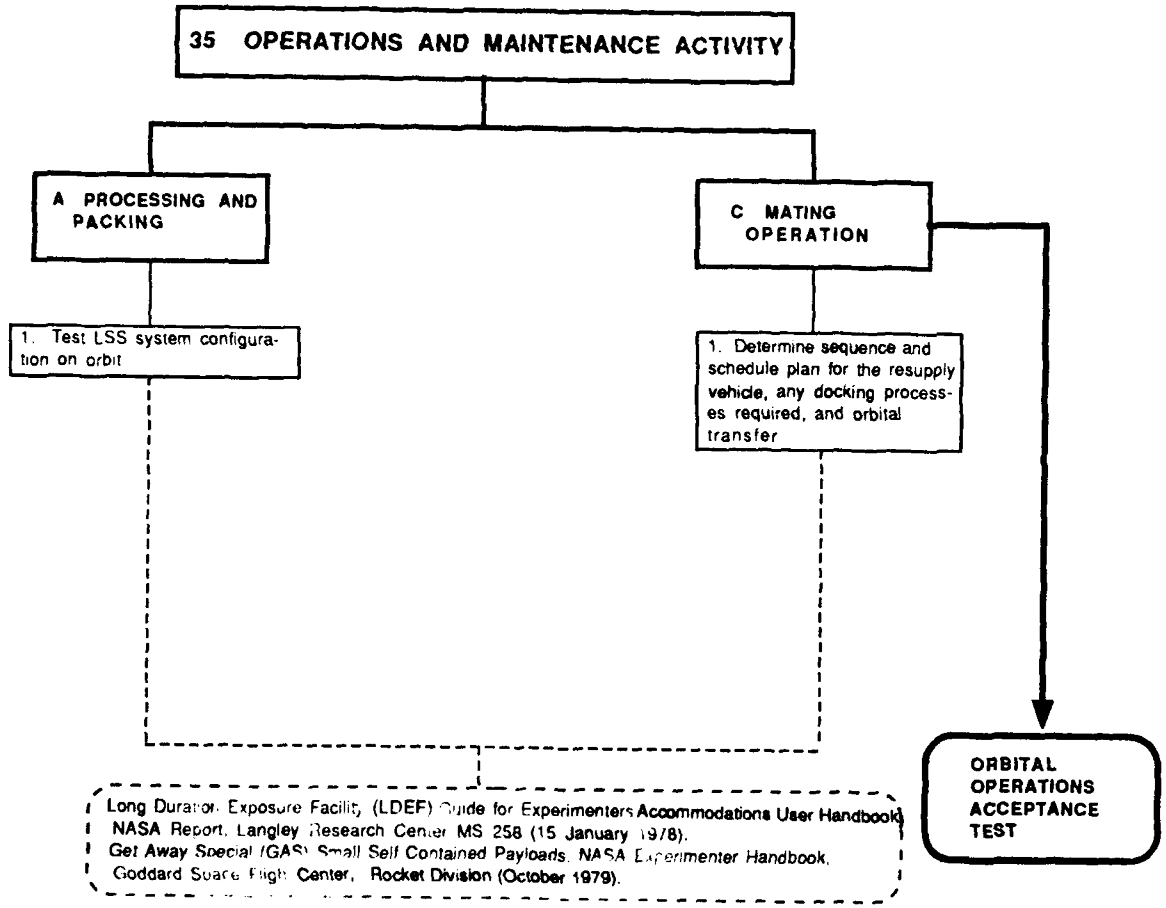
35 OPERATIONS AND MAINTENANCE ACTIVITY

A. Operations

1. Test LSS system configuration on orbit

B. Maintenance Analysis

1. Determine sequence and schedule plan for the resupply vehicle, any docking processes required, and orbital transfer maneuvers



a. Flow chart

Figure 8. 35 Operations and Maintenance Activity.

CODE	ACTIVITY	WHO IS BEST QUALIFIED TO ACCOMPLISH TASK?	RESPONSIBLE ENTITY	EST. $	WHEN IS THE BEST TIME TO DO IT?	DURATION EST.	DURATION ACT.	CRITICAL STATUS?	PRIMARY REFERENCES	NOTES
A	Operations									
B	Maintenance Analysis									
MILESTONE 7: ORBITAL OPERATIONS LSS ACCEPTANCE TEST										

b. Spreadsheet

Figure 8. (Cont'd).

4 CONCLUSIONS AND RECOMMENDATIONS

A plan has been proposed for fielding LSS. The plan includes logical sequences of activities and identifies the interface/integration points that must be addressed.

This fielding plan should be used as the basis for compiling an automated program that can be updated and expanded as necessary for efficiency. In addition, careful consideration should be given to forming a space construction data bank to contain an organized, systematic set of information and design data for LSS project engineers and managers.

Many elements within the fielding plan lack supporting reference documents. Studies are needed to fill these voids.

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Terms and Abbreviations

Terms

Construction loop integration: user developed scenario which integrates all EVA and automation for LSS assembly; written plan and interface to all other documents

Construction loop verification: identification and integration of assembly simulations to provide accurate ground test for LSS assembly sequence, including test and analysis results

Data requirements listing: list of required documents which describe the LSS concept and all decision logic and criteria available at the time. It consists of drawings, materials, schematics, and safety analysis; the documents should be provided by the LSS sponsor.

Cost/risk analyses: must be performed early in design process, since erectable/deployable variables and lift vehicle criteria will affect LSS costs

Integration analysis document: by LSS sponsor to define level of confidence and required testing for parts which will be mated into overall LSS system during construction in orbit

Large space structural orbital test plan: LSS sponsor developed; must be designed for QC/QA since nothing of this scale has been designed and flown

Terms and Abbreviations (Cont'd)

Operations and maintenance plan: user developed document with emphasis on resupply mission and schedule for maintenance on orbit, including cost estimates

Subsystem criteria: generic and DOD standards that exist for some components; for most LSS systems, new standards must be defined and fabrication criteria developed

Abbreviations

EVA: extravehicular activity

QA: quality assurance

QC: quality control

APPENDIX:

SPREADSHEET KEY

Title - at top of page designates the work phase with the assigned work number. Seven (7) work phases have been identified from the fielding plan thus far, however addition/expansion as new work areas are identified is possible.

Code - the alphabetic code assigned to all the activities comprising a specific work phase (A-Z).

Who is best qualified to accomplish task?
This is a question of operational management. Obviously, the person or group which specializes in that particular area is best qualified. However, some tasks for LSS construction and operations are state-of-the-art and therefore have no parameters or precedence by which to determine who or what group is best qualified to execute it.

Responsible Entity
This question addresses the identification of the major or parent entities involved with the specific activity (i.e. NASA, DOD, Army Corps of Engineers, etc...). Some responsibilities for activities may be joint efforts and will be identified as such.

Estimated Costs ($)?
This area is designed to address rough estimates of the total costs associated with executing the activity. Whether or not this is an issue that should be accessible by other users of the automated fielding plan is in question.

When is the best time to do it?
The parameter of the term "when" addresses questions of precedence with the work phases, activities, and tasks in the scope of the entire fielding plan. Also, this question should include concerns about ground based testing or testing on orbit.

Duration
Examines how long it will take to execute (at the activity level) in terms of days/months/years beginning with the estimated duration noted next to the actual duration to be filled in at a later date. Because research in this area is in its infancy, it is difficult to address the activities using time as a parameter at this point. This can be filled in as research advances.

Critical Status?
Examines the activity in terms of the entire plan. Asks whether or not a particular task must be completed before moving on to the next activity and ultimately the next work phase. If the plan cannot move into the next work phase until the this activity is completed, then it is considered to have **critical** status.

Primary References
If reference material exists on a particular activity - the primary sources will be noted. A reference library database must be created and keyed to the automated fielding plan so that each reference can be assigned an alpha-numeric code to be used as a citation.

Notes
Documents any pertinent information or extenuating circumstances not covered in the given categories.

Milestone - (located in bottom left corner of spreadsheet) indicates that a review has been performed and all activities and tasks of the work phase have been completed and no loops need to occur (if a discrepancy occurs, it can be identified and addressed using a loop format thus eliminating the need to always start from the beginning of the work phase). If there are no discrepancies, the completion of the milestone gives the signal to move on the next work phase. The following are decision point milestones for each work phase in the LSS fielding plan.

1. Preliminary Design Review
2. Critical LSS Systems Design Review
3. Launch Team Review and Analysis
4. Launch Team Critical Integration Review
5. Launch
6. Construction Completion
7. Orbital Operations LSS Acceptance Test

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